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13. ABSTRACT (Maximum 200 words)

An embeddable structural health monitoring system has been developed to measure acoustic emission signals generated by incipient damage in Army structures. The structural health monitoring system is built upon two parallel approaches that mimic signal processing in biological nerve cells. One approach uses a continuous sensor formed by a series connection of piezoelectric sensor nodes and a local signal processor to detect damage. The other uses an array type of sensor with appropriate electronics for quantifying damage. Modeling of wave propagation in simple structural elements was performed and the electrical responses of the sensors were simulated. Coupon specimens and panels were also instrumented with the two types of sensors and tested in the laboratory. The simulation and experimental results both confirmed the advantages offered by these sensors for structural health monitoring applications. A prototype of the acoustic emission local processor was also fabricated, and detailed specifications for implementing the algorithms developed in this project into an embeddable VLSI chip are provided. This project resulted in two U.S. patent applications, of which one has already been granted, and two invention disclosures. Commercialization of this technology is currently being pursued.

14. SUBJECT TERMS

Structural health monitoring, acoustic emissions, artificial neural system

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1. STATEMENT OF THE PROBLEM STUDIED

The objective of this project was to design, build, and test a neural composite material. The neural composite material is envisioned as a material that incorporates embedded and interconnected sensory system with tens or even hundreds of unit cells that can autonomously monitor the integrity of the structural material. These unit cells are built by integrating three key components: (i) the “continuous sensor” that is formed by connecting up to 15 PZT sensor nodes in series – to function as a distributed acoustic emission (AE) sensor, (ii) a local processor that acquires and quantifies the AE signals, and (iii) an interface that transmits the information gathered by the local processor over a digital sensor bus to the central computer. The work summarized below was performed through collaboration between three different universities and a private industrial partner. The principal investigators and their respective institutions were: Mannur Sundaresan - North Carolina A&T State University, Mark Schulz - University of Cincinnati, Promod Pratap - University of North Carolina at Greensboro, and James Kemerling - Triad Semiconductor Inc.

2. SUMMARY OF IMPORTANT RESULTS

This project was to develop a neural composite material that can continuously monitor its own integrity and detect any damage occurring to the material. The approach taken was to develop a continuous sensor to measure acoustic emission signals that are produced when damage occurs in the material, and to develop a biomimetic signal processing architecture to efficiently process the signals from the continuous sensors. A continuous sensor was formed by connecting multiple sensors nodes in series so that the individual sensor responses are combined into a single electrical output signal. Figure 1 illustrates the formation of a continuous sensor and compares the instrumentation that uses the continuous sensor with that of a traditional AE sensor. The continuous sensor can provide a significant increase in sensitivity while simultaneously reducing the number of instrumentation channels. The performance of the continuous sensor has been evaluated using simulated AE signals as well as real flaw growth in metallic and composite materials [1-3].

In addition to this simplification, a unit cell shown in Figure 1(b) was designed to further enhance the adaptability of the sensor system for weight critical applications such as those in aircraft or space applications. The unit cell contains an embeddable local processor placed near the sensor nodes to perform the analog signal conditioning, including amplification and filtering, as well as the digital signal processing to extract the main attributes of the detected acoustic emission signal [5]. The signal processing will reduce the high volume input data into a compact set of AE parameters only about ten bytes long for each AE event. The micro miniaturization of electronics makes it possible to fabricate such an embeddable processor using current technology. The illustration shown in Figure 1(b) includes an array of three such unit cells, with each unit cell containing 9 sensor nodes and a local processor. These local processors will also communicate with a central processor over a digital bus and periodically upload

processed information to the central computer.

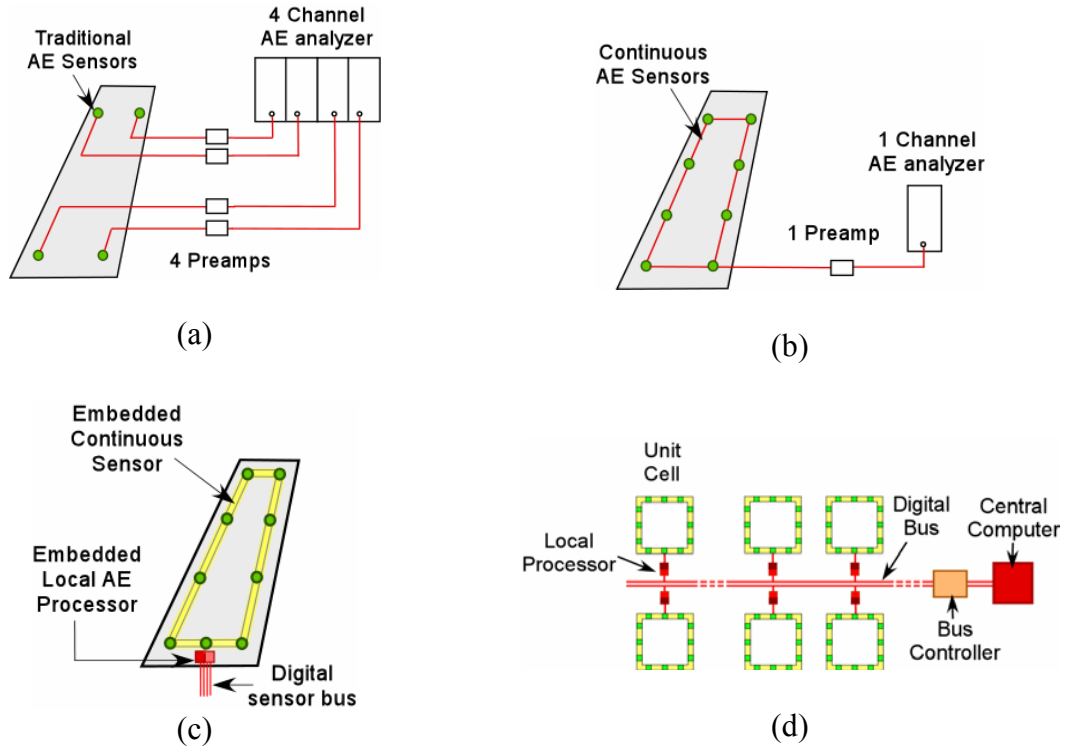


Figure 1. structural health monitoring system based on continuous sensor; (a) A traditional single node AE sensor system, (b) An AE system that uses eight-node continuous sensor, (c) The unit cell of a SHM system with continuous sensor and an embeddable signal processing chip, and (d) The integration of several unit cells and a sensor bus for monitoring the health structure.

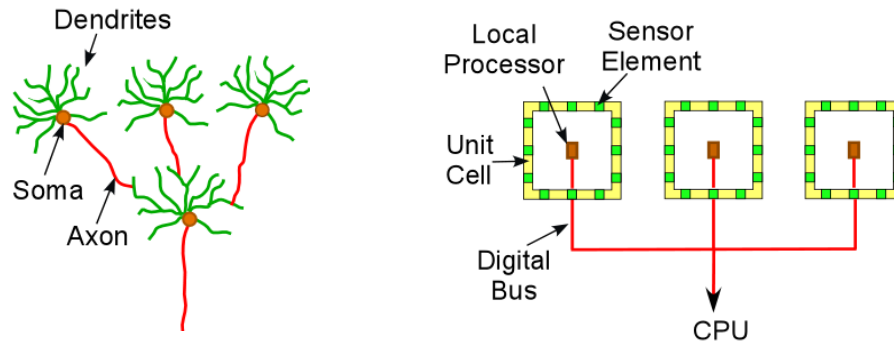


Figure 2. Unit cells of the structural health monitoring system; (a) Simplified illustration of the biological nervous system, (b) Unit cells with autonomous sensing, signal processing, and communication capability that are similar to individual nerve cells.

As illustrated in Figure 2, the unit cells retain the simplicity and scalability of the biological nerve cells, and hence this approach is attractive for building health monitoring systems for large and complex structures. The first generation of local processors developed in the project have the most basic functions required for measuring the damage growth in the region covered by the unit cell. Further refinements will be introduced at a later stage.

For implementing these concepts in the laboratory environment and to demonstrate the feasibility of developing an embeddable structural health monitoring system, a prototype of the local processor was developed [4]. This prototype was developed by Triad Semiconductor Inc. under a subcontract from the ARO project. This prototype includes all the functions of the embeddable local processor, but is built using off-the-shelf electronic hardware and software, and emulates the working of the embeddable local processor. A laptop computer performs the emulations. Figure 3 shows a picture of this prototype.

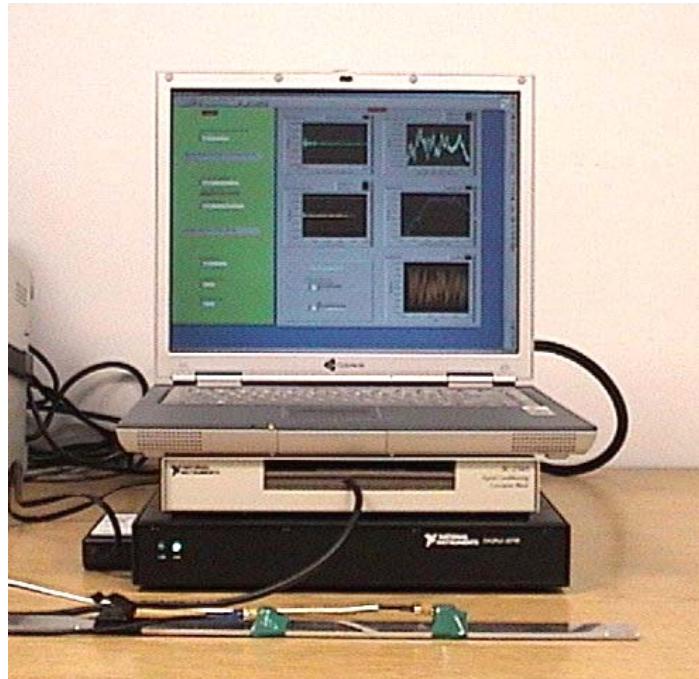


Figure 3. Prototype of the AE local processor.

In this project, work was also started to develop an array Artificial Neural System (ANS) [5-7]. The array ANS, pictured in Figure 4, uses continuous sensor neurons and analog processors at each neuron to mimic the firing and thresholding functions of biological systems. The array ANS monitors a large number of neurons in real-time and uses individual neuron “firing” to pass signals only when and where damage is detected. This approach provides highly distributed sensing and massively parallel signal processing using analog signals, similar to biological systems. The A/D conversion is only needed at the PC level, and this reduces the complexity of the instrumentation and the cost, size,

and weight of the SHM system. It is anticipated that continued development of the array ANS will lead to ultra-high-density high-sensitivity sensor systems that can be built at either the macroscopic or the microscopic scale. The ANS architecture may also have applications in health monitoring of living systems and the environment.

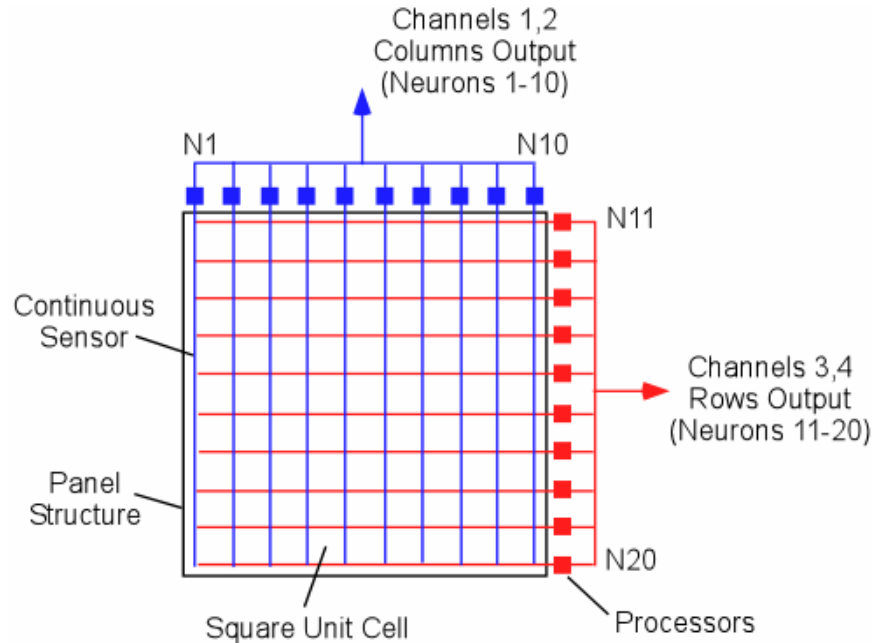


Figure 4. An array ANS with ten row and ten column neurons (N1-N20) which are continuous sensors that sense along their entire length; the row and column neurons in the array are routed into four signal channels - two channels of time signals, and two channels for neuron firing; using information from these four channels, it is possible to locate the AE source and measure the signal amplitude.

The development of the continuous sensor based instrumentation into a practical health monitoring system was split into a number of steps. The main tasks in this development were; (i) Numerical simulation of wave propagation in simple structural elements and modeling of the resulting signals from the embedded sensors, (ii) Experimental determination of the performance of the continuous sensor using simulated acoustic emission signals, (iii) Experimental evaluation of the performance of the continuous sensor on coupon specimens and a composite panel, (iv) Development of algorithms for location of an acoustic emission source using a single channel continuous sensor and their experimental verification, (v) Development of wavelet based signal processing techniques for understanding the characteristics of acoustic emission signals, (vi) Development of a new array type of sensor configuration, (vii) Development of procedures for processing signals from the array type of sensor, (viii) Development of a prototype of the local processor using discrete components, and (ix) Development of the detailed specifications for the local processor chip. These steps are summarized below as tasks performed.

2.1 TASKS PERFORMED

1. Numerical simulation of wave propagation in simple structural elements and modeling of the resulting signals from the embedded sensors: An active fiber composite tape with segmented electrodes was modeled for use as a continuous sensor for structural health monitoring of plate structures. The material has unidirectional Piezoceramic fibers with interdigital electrodes on the top and bottom surfaces and is poled in the fiber direction. The elastic response of a plate with the modeled sensor was computed in closed form in small time steps and the coupled Piezoceramic constitutive equations were solved. Wave propagation responses and the corresponding sensor voltages were computed in the simulations. The simulations indicate that the continuous sensor can detect damage to the plate based on high frequency wave propagation characteristics [1, 8]. Wave propagation in coupon specimen and the corresponding signal from a five-node continuous sensor bonded to the specimen were also modeled [9].

2. Experimental determination of the performance of continuous sensor using simulated acoustic emission signals: A continuous sensor comprised of nine monolithic piezoceramic patches was built and tested to measure simulated acoustic emission on a composite panel. The monolithic patches were used to simplify the fabrication of sensor. The continuous sensor was found to retain both the frequency and amplitude characteristics of a single node sensor located close the AE source. In addition, the continuous sensor detected simulated acoustic emissions occurring anywhere in the panel using only one channel of data acquisition. In comparison, traditional single node sensor could detect AE signals and in particular high frequency components of the AE signal only when the source is located close the sensor [8].

3. Experimental evaluation of the performance of continuous sensor on coupon specimens and a composite panel: Acoustic emission signals from fatigue cracks in aluminum and composite samples were compared. In aluminum specimens very little attenuation of frequency components in the range of 100 KHz to 200 KHz was seen within propagation distances of the order of 10", whereas significant attenuation of these frequency components was seen in woven glass epoxy specimen [9]. High levels of signal attenuation is one of the factors that can render conventional acoustic emission instrumentation as well as Lamb wave based instrumentation impractical for structures built from composite materials and in those situations the continuous sensor is likely to provide distinct advantages.

Coupon specimens with a three-node continuous sensor bonded to the specimen surface were fabricated. The performance of this continuous sensor in monitoring fatigue crack growth in these specimens was compared with that of a conventional single node wide band sensor. The continuous sensor survived several tens of thousands of cycles of fatigue load and had higher sensitivity compared to the single node sensor [10].

The continuous sensor was used to monitor fatigue crack extensions in a glass epoxy composite panel. The sensor was found to be sufficiently sensitive to detect fatigue crack growth rates of the order of 4×10^{-6} inch/cycle. The waveforms from the mode I type crack growth had some differences. Based on these differences nine different AE signal

types were identified and their relative frequency components were examined. Further, a continuous sensor with its distributed sensing nodes was shown to be superior to traditional single node acoustic emission sensors for this panel specimen [4].

4. Development and experimental verification of algorithms for location of an acoustic emission source using a single channel continuous sensor: The signals sensed by the individual sensor nodes are superposed and hence mixed for a continuous sensor. Hence, at first sight, it appears that all location information about the AE source may be lost because of this superposition of signals from several sensor nodes. However, it was found that in some situations it is possible to extract the location information from the single channel continuous sensor output. This was demonstrated both numerically and experimentally for linear location on a bar [2]. A Lamb wave mode with minimum dispersion was selected for the purpose of location, and through suitable filtering of the continuous sensor output, it is possible to separate individual pulses corresponding to this mode arriving at each of the sensor nodes. Using this information and the sensor location, the AE sources were located. A similar procedure was shown to work for locating an AE source in a two-dimensional plane, in numerical simulations.

5. Development of wavelet based signal-processing techniques for understanding the characteristics of acoustic emission signals: AE signals are comprised of several Lamb wave modes traveling together in the structure. These modes travel with differing velocities and reflect from the boundaries and other features in the structure. Hence, the quantitative interpretation of the AE signal in general and relating the AE signal amplitude to the damage event in particular requires a good understanding of the different components present in the AE signal. For this purpose, the procedure of visualizing the time-frequency information in the AE signal through wavelet analysis was used [4]. This procedure was used to examine the signal characteristics of both simulated AE signals, AE signals due to fatigue crack growth in aluminum and glass-epoxy coupon specimens, and in a glass epoxy panel [11].

6. Development of a new array type of sensor configuration- Results from numerical simulation and experiments: The numerical simulation program used for evaluating the continuous sensor was modified to include half-sine impulse excitation to represent AE sources. In addition, the equations of wave propagation were modified to represent the orthotropic material characteristics corresponding to a cross-ply composite laminate. This model allowed tailoring the input to represent different types of damage. For example, an impact with any period can be modeled, as well as tone bursts, impulses, and sine waves. The numerical simulation also modeled the array type of sensor described in the introduction. The sensor nodes corresponding to the array were modeled as being attached to a composite panel. The extraction of the AE source location from the four-channel system was simulated through the appropriate firing of the “neurons.” The simulations showed that the ANS could detect simulated damage anywhere in the panel [5-7]. The use of a neural network for processing the signals from an array type of sensor and extracting the location information was also explored [12].

7. Development of procedures for processing signals from the array type of sensor:

A procedure for extracting information about both the location of the AE source and the signal amplitude as sensed by the closest sensor nodes was developed. An array type of sensor system with two rows and two columns was built and tested on a composite panel. This testing used four channels of data acquisition and the computer was used to represent the functions of the neural system including firing of the neurons. This array sensor was able to detect simulated AE using a lead break anywhere in the panel [5-7].

8. Development of a prototype of the local processor using discrete components:

A PC based simulator/emulator (using custom software and off-the-shelf data acquisition hardware) has been developed as a means to determine the viability of the continuous sensor/AE local processor combination in a SHM system. To minimize development time and simplify reprogramming, the software platform "LabView" by National Instruments was used. LabView provides a graphical programming environment to facilitate the implementation of the local processor's signal processing algorithms. In addition, LabView interfaces directly with the data acquisition hardware, which, in this case, is a high-speed analog-to-digital converter (ADC) with custom external analog signal conditioning. Finally, the LabView based system allows algorithms to be easily and quickly be modified to accommodate unexpected conditions in the field [WSHM]. The hardware consists of a signal conditioning gain stage, an anti-aliasing filter, an ADC, a laptop and the transducer bus interface module. The laptop is responsible for emulating the function of the local processor. The local processor soft model performs the tasks of acquiring data from the external ADC, processing/compressing the data, and formatting the data for transmission. This soft model contains all the functions necessary to implement the local processor for structural health monitoring applications. This effort was supported by funds under this grant as well as funds leveraged from other sources.

9. Development of the detailed specifications for the local processor chip: The specification is the first stage of the design and development of the VLSI chip that is required for the structural health monitoring system. Triad Semiconductor Inc. developed this specification under a subcontract from NC A&T SU as a part of the current project. A significant effort was spent on the development of the specification and it covers all the requirements of the local processor in sufficient detail such that a reasonably competent design team will be able to carry out the implementation and build the required VLSI chip. This specification serves as the primary reference throughout the development of the Local processor project. It includes a high-level description of the functional blocks and how they must be integrated to realize the VLSI.

10. Technology Transfer:

A. A new journal entitled "Structural Health Monitoring: An International Journal," started July 2002. The Editor-in-Chief of the journal is Fuo-Kuo Chang of Stanford University, the Managing Editor is Mark Schulz from the UC, and the Scientific Editor is William H. Prosser of NASA Langley Research Center. Mannur J. Sundaresan of NCA&TSU and Dr. Gary Anderson of the ARO are two of the Associate Editors of the journal. Sage Publishing Company publishes the journal. The new journal was originated at NCA&TSU partly due to the support of the ARO.

B. The commercialization of the technology developed under this grant is being pursued in collaboration with “Triad Semiconductor,” a local company located at Winston-Salem.

C. A new patent titled “Continuous Acoustic Emission and Vibration Sensor,” U.S. Patent number 6,399,939, has been obtained.

Another patent titled “Linear Location of Acoustic Emission Sources with a Single Channel Distributed Sensor,” is pending.

The following two inventions disclosures also resulted from the work performed under this grant: “An Artificial Neural System,” Invention Disclosure, U. of Cincinnati, 8/26/03, UC-103-046. and “An Active Fiber Continuous Sensor,” Invention Disclosure, University of Cincinnati, 7/21/03, UC 103-034.

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I. Papers published in peer reviewed journals:

1. Schulz, M.J., Sundaresan, M., McMichael, J., Clayton, D., Sadler, R., Nagel, W., "Piezoelectric Materials at Elevated Temperature," in press, J. Intelligent Material Systems and Structures.
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II. Papers published in conference proceedings:

1. M. J. Sundaresan, G. Grandhi, L. Uitenham, M. J. Schulz, J. Kemerling, D. Hughes, Development of an Acoustic Emission Based Structural Health Monitoring System, Fourth International Workshop on Structural Health Monitoring, September 15-17, 2003, Stanford University, CA.
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III. Papers Presented in conferences:

1. Mannur J. Sundaresan, Gangadhararao Grandhi, Mark J. Schulz, "A Structural Health Monitoring System Based On Continuous Acoustic Emission Sensors," Quantitative Nondestructive Evaluation Conference, KI Convention Center, Green Bay, Wisconsin, July 27-August 1, 2003.

2. Sundaresan, M.J., G. Grandhi, J. Kemerling, S. Uppaluri M. Schulz, D. Hughes, "Monitoring Damage Growth in a Composite Panel Using Continuous Sensor", AeroMat03, June 10, 2003, Dayton, OH.

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6. REPORT OF INVENTIONS

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